DEVELOPMENT OF RECOMMENDATIONS FOR THE IMPLEMENTATION OF COMBINED DEFORMATION TREATMENT "ECAP-DRAWING" INTO PRODUCTION

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ABSTRACT

Combined innovative technology developed in this article makes it possible to produce bimetallic long products in the form of bars and wires with improved mechanical properties, due to the ultrafine grain structure of the material, with less energy and labor costs and implementation of continuity principle in industrial enterprises of metal-working industry. The combination of equal-channel angular pressing with drawing makes it possible not only to harden the composition, but at the same time to preserve important and regulated by a number of GOST plastic properties of the products. This circumstance favorably distinguishes the method under study from other (traditional) types of deformation treatment.

Keywords: *severe plastic deformation, bimetallic wire, technology, ECAP-drawing, ultrafine grain structure.*

INTRODUCTION

One common method of strain-hardening bimetallic wire is the classic drawing process. The wire drawing process includes an alternation of operations: heat treatment, surface preparation and straining in the drawing machine. These operations reduce the cross-section and achieve the necessary properties required by the technical requirements. After straining, the metal acquires a fibrous structure, which includes strain texture. The number of alternating technological operations may vary depending on the diameter of finished wire and the plasticity of metal [1 - 3]. A prerequisite for drawing dissimilar materials together is reliable adhesion at the interface between the strained phases (reliable welding of bimetal components).

Poor welding can lead to a number of defects: lapping (slippage of the soft outer layer); local thinning of the core which can make the wire surface wavy; breaks in the less ductile metal. Laps and breaks lead to wire breaks during drawing. In addition, breaks in the core or casing layer are stress concentrators and greatly reduce the quality of the wire making it brittle. Local thinning of the steel core reduces the tensile strength of the wire [4]. Breaks in the rigid component of bimetal are possible only if there is a certain ratio of the components that make up the bimetal. If the soft component content is low, wire breaks due to uneven strain are impossible;

but if the content is high, the wire will break during the drawing process.

Therefore, at least two conditions must be fulfilled for plastic deformation of dissimilar metals:

1) The greater the strain energy of the softer metal, the greater the possibility of fracture of the harder and less ductile metal, so the soft component content must be minimal.

2) An unfavourable stress pattern must be created by the choice of strain magnitude and working tool geometry in order to make the deformation conditions of the soft component as difficult as possible.

It has been established in practice [5, 6] that if the core has a small plasticity margin as compared to the casing and if the thickness of the casing is significant, it is necessary to draw with reduced rates as compared to the set single core reduction. For thin films, high reduction rates should be applied. Similarly, the total reduction is set. With small single reductions, even with sufficiently strong cores and thick casings (coatings), it is possible to successfully draw with significant total reductions.

Modern studies of mechanics of cold drawing of monometallic wire provide a comprehensive picture of the influence of basic parameters on the main process. Combining experimental data with theoretical and numerical models of basic friction and strain can effectively provide a production planning procedure and produce principles for controlling the production process of drawing. Many aspects of complex phenomena occurring in the drawing of monometallic wire have been extensively covered in comprehensive theoretical [7, 8] and experimental [9, 10] studies on basic modeling of straining process and analysis of the influence of the main parameters. Studies of drawing machine geometry, material properties, and contact friction have led to a detailed description of drawing mechanics [6] and aspects of central continuity gaps characteristic of wire drawing and often caused by the growth of internal voids under critical process conditions. However, for bimetallic wires, the scientific basis for the design of the drawing process has not yet been created.

One of the promising areas of plastic strain-hardening of bimetallic wire is the ECAD process (equal-channel angular drawing) [11]. According to the proposed method, the steel-copper wire is repeatedly pulled through a prefabricated tool with a special profile. The key difference between the proposed method and most of the existing deformation schemes for the formation of UFG structures is the possibility of using the process in mass production of the hardware industry. Continuity of deformation treatment can be achieved by a combination of ECAD with the traditional method of wire drawing.

The authors conducted a study for the effect of multiple (up to 10 times) ECAD on the evolution of the structure and changes in properties of core diameter 5.5, 5.0, 4.5, and 4.2 mm (steel grade 10), which determines the strength of steel-metal wire [11]. It is shown that ECAD is accompanied by a significant fragmentation of structural components of the surface and central area of the samples, regardless of their diameter. Even after N = 2 and up to N = 10 machining cycles an intensive grinding of the wire structure is observed.

There is a technology of bimetallic wire drawing developed by specialists at Magnitogorsk State Technical University named after G.I. Nosov, which is a fundamentally new continuous method of free drawing in curved channels [12, 13]. In this method, the wire is repeatedly pulled through a composite drawing plate of special design, which leads to single-axis elongation and bending of the wire, simultaneously in two directions. This provides non-monotonic strain and facilitates significant fragmentation of the component structure. In this method, the tool is not solidly filled with wire, which maintains a constant cross-section and passes sequentially through the following zones. Free drawing in curved channels differs from the best-known deformation methods of shaping ultrafine grains in the sense that it is suitable for producing long products and can be integrated into existing production lines.

Another continuous method of bimetallic wire straining is developed at Magnitogorsk State Technical University named after G.I. Nosov. The method is based on the combination of tensile strain, and bending strain in the roller system, combined in the drive module with the possibility of rotation and implementation of torsional strain [14, 15]. The main process parameters affect the ultrafine grain structure and mechanical properties of bimetallic wire.

The quality of steel-copper wire depends on mechanical properties of the steel core, which determine the strainability of the bimetallic composite and the adhesion strength of two components. By evaluating the effect of this processing method on the mechanical properties of steel-copper wire, we can not only correctly select the strain conditions, but also predict the properties of products obtained using ultradisperse materials.

One of the known methods of strain-hardening of bimetallic copper-steel and copper-aluminum bars is the process of rolling in the oval-cutting oval gauge system [16]. As a result of rolling in six passes, rods with a diameter of about 14.0 mm were obtained. The system consists of six horizontal gauges: oval-rib and oval-circle. After each pass, the workpiece was turned by an angle of 90°. During rolling, the thickness of copper layer decreased by 1 - 4 % compared to the rod after explosion welding. The developed technology of bimetallic rod rolling has shown that a properly performed rolling process guarantees a high-quality bimetallic product with comparable adhesion quality of the components.

There is a method of strain-hardening a bimetallic aluminum-copper composite using equal-channel angular pressing [17]. Among the various molding processes used to produce a bimetallic core, equal channel angular pressing (ECAP) is unique because of several advantages, such as dimensional accuracy, shear strain realization, simple die shape.

However, despite numerous developments, the problem of creating a new deformation scheme, as close as possible to industrial conditions and of scientific and practical interest in terms of mass production remains unresolved. One of such schemes could be a new continuous scheme of equal-channel angular pressing - drawing (ECAP-drawing) [18].

Its key feature is that, unlike other combined methods, there is no rolling stage. Continuity of deformation is ensured by the drawing process that comes immediately after ECAP process.

Because of this unique deformation scheme, a sufficiently high level of tensile stresses develops in the cross-section of the workpiece, and the wrong selection of process parameters will lead to a break of strained wire.

The most suitable method on the basis of which it is possible to develop a technology suitable for industrial conversion of bimetallic wire and bar with improved mechanical properties is ECAP-drawing. To date, many studies of the structure-property relationship for homogeneous copper and steel wires, as well as bimetallic wires, have been conducted by this method, which has proven to be effective [19 - 22].

This paper, based on the already large number of studies, gives the development of recommendations for the implementation of combined deformation treatment “ECAP-drawing” in production and developed table with modes of bimetallic wire strain.

EXPERIMENTAL

The initial billet was a bimetallic wire purchased from a third party, consisting of a steel core - AISI-1010 and an outer layer of AA 1135 aluminium. The original wire had a diameter of 10 mm and the steel core had a diameter of 8 mm.

The physical experiment was carried out on a B-1/550 M semi-industrial drawing mill, according to the method described in [19, 21]. Deformation by RCUP-drawing was carried out in three passes at room temperature.

RESULTS AND DISCUSSION

The implementation of new technology of combined process “ECAP-drawing” will require the use of additional tooling - equal-channel stepped matrix of special design, which is shown in Fig. 1.

It is recommended to make the equal-channel stepped matrix from tool stamping steel 5XV2S. To increase the hardness and strength of the matrix, a heat treatment technology has been developed. It includes quenching at a temperature regime that corresponds to the selected steel

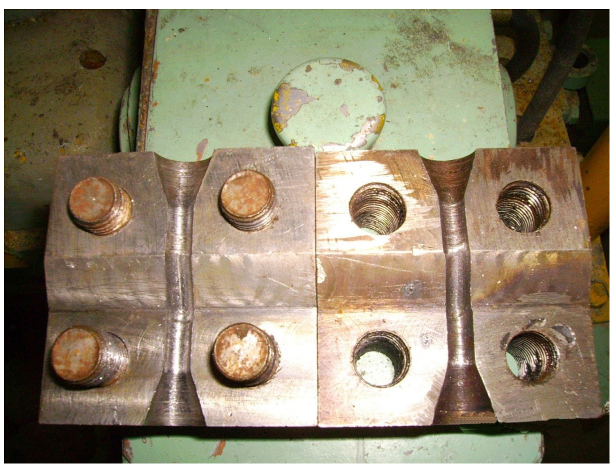

Fig. 1. Equal-channel stepped die.

grade. Pass diameter of the channel is selected according to the given diameter of a workpiece subjected to the drawing process. Dimensions of channel lengths and channel junction angle are selected in accordance with the developed drawing shown in Fig. 2.

The technical documentation on matrix design was based on the results of theoretical research and modeling in the Deform software package [22, 23]. Channel junction angle and channel lengths provide the most favorable stress-strain state for obtaining ultrafine grained structure and minimum values of energy-power parameters during bimetallic wire and rod straining.

To implement the combined process of ECAP-drawing, it is advisable to make the equal-channel step matrix separate and place it in the lubrication chamber before the node with the die. Soap chips shall be used as a lubricant, just as in conventional drawing. Achievement of increased mechanical characteristics and preservation of plastic properties is possible with multi-cycle straining. To implement this combined process, it is possible to conduct according to the scheme proposed in this paper and perform a change of matrices for each cycle of strain.

To charge bimetallic wire or rod into an equal-channel stepped matrix and to exclude breakage, it is necessary to use a setting (charging) device when carrying out the combined ECAP-drawing process. To charge rods and wires into the matrix, it is possible to use the rebuilt sharpening machine of the drawing mill. For this purpose, the machine can be rephased so that the rollers rotate in the opposite direction, which results in capturing the wire and pushing it into the equal-channel stepped matrix due to the active friction forces. One of the main conditions for the successful implementation of combined ECAP-drawing process is the obligatory coordination of speeds of pushing and pulling of bimetallic wire or rod.

Processing technology of bimetallic bars and wires by a new developed technology on the equipment of the drawing mill is carried out by the following technological operations: a coil holder is hung up with the help of shop vehicles with a bunch of workpieces, prepared for the drawing process (for the process of drawing bimetallic wires). The lower end of the wire is pulled from the bunghole to the sharpening machine for sharpening. The end of the wire is sharpened on the sharpening machine to the required diameter and length of 150 - 180 mm. The sharpened wire end is fed to the spooling unit, which guides the wire into the forming die mounted in the mandrel through an equal-channel stepped matrix. The wire is then gripped by the filling tongs (Fig. 3) and the machine is switched on. The foot pedal jogs the machine at filling speed (triggering the doffing unit at the same time). When 5 - 7 coils have been wound onto the drum, the machine is stopped. Then the threading tongs are removed and the end of the wire is fastened firmly to one of the racks of the drum. Then the machine and the spooling device are switched on at a pre-set technological speed and work until the drum is filled.

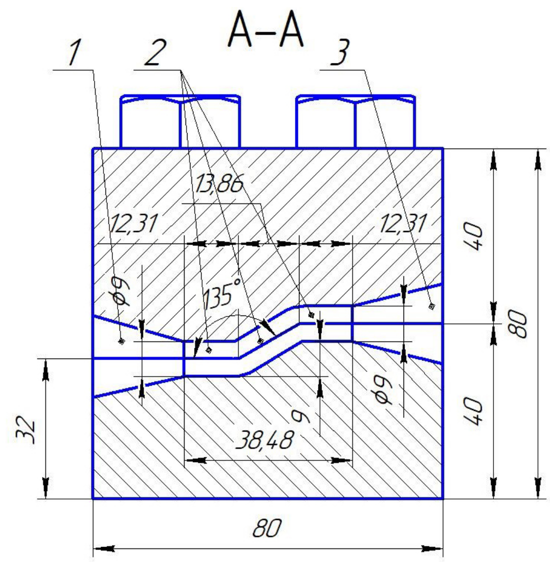

Fig. 2. Drawing of an equal-channel stepped die.


Fig. 3. Clamping the bar in the drawing tongs.

The machine is stopped after the drum is filled. Then they reverse the drum for 2 - 3 turns, the wire is cut between the mandrel and the drum, and finished wire is removed

Table 1. Bimetal strain mode.

ECAP					Drawing								
No. of pass	D_0, mm	V_0, m sec^{-1}	F_0, mm^2	ε_{ln}	D_1, mm	D_2, mm	λ	V_2, m sec^{-1}	V_1, m sec^{-1}	ε, %	F_1, mm^2	F_2, mm^2	ε_{ln}
1 pass	10.0	1.29	78.50	0.61	10.00	9.50	1.11	1.43	1.29	9.75	78.50	70.85	0.09
2 pass	9.5	1.28	70.85	1.21	9.50	9.00	1.11	1.43	1.28	10.25	70.85	63.59	0.10
3 pass	9.0	1.28	63.59	1.82	9.00	8.50	1.12	1.43	1.28	10.80	63.59	56.72	0.10
ε_{ln}(total)				1.82				ε(total), %		27.75	ε_{ln}(total)		0.24
ε_{ln}(total) = 2.06													

from the drum by a crane onto a rack. The mill is controlled from the control panel.

It is recommended to use strain mode given in Table 1 in case of multi-cycle combined process “ECAP- drawing” and after each cycle of straining it is necessary to change equal-channel stepped matrix in the lubricating container and in the die holder for drawing to a lesser diameter.

To implement the combined process of ECAP-drawing of bimetallic bars, on the basis of chain drawing mill, the end of workpiece is sharpened on the sharpening machine. After completing all the preparatory operations, which include the input of lubricant into the inlet and outlet channels of equal-channel stepped matrix and charging the wire in equal-channel stepped matrix, the workpiece is passed through the die and gripped by special vice installed on the trolley which has a hook on the other side to connect to the chain. When starting the unit, the trolley with the vice on four rollers moves along the body, pulling the bimetal bar gripped by the clamps behind it.

CONCLUSIONS

This technology of metal processing can be used to produce high-quality bimetallic wire and rods from various combinations of non-ferrous metals and alloys. Developed deformation method being implemented in production does not require significant technical and economic investments and can be implemented in the technological lines of industrial enterprises of the Republic of Kazakhstan for the production of bimetallic wire and rods, as it does not require significant re-equipment of drawing mills, but only supplements their existing equipment, adding to the design of equipment specially made equal-channel stepped matrix.

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REFERENCES

1. N. Zhangabay, B. Sapargaliyeva, A. Utelbayeva, A. Kolesnikov, Z. Aldiyarov, S. Dossybekov, E. Esimov, B. Duissenbekov, R. Fediuk, N. Vatin, M. Yermakhanov, S. Mussayeva. Experimental Analysis of the Stress State of a Prestressed Cylindrical Shell with Various Structural Parameters. Materials, 15, 2022, 4996.
2. H. Dyja, L. Lesik, A. Milenin, S. Mróz, Theoretical and experimental analysis of stress and temperature distributions during the process of rolling bimetallic rods, J. Mater. Process. Technol., 2002, 125-126, 731-735.
3. I. Volokitina, Structure and mechanical properties of aluminum alloy 2024 after cryogenic cooling during ECAP, J. Chem. Technol. Metall., 55, 3, 2020, 580-585.
4. A.L. Tarnavskiy, V.V. Gurylev, B.B. Shchurovskiy, Bimetallic wire, Moscow, Metallurgizdat, 1963, p. 124, (in Russian).
5. I.L. Perlin, M.Z. Ermanok, Drawing theory, Moscow, Metallurgy, 1971, p. 448, (in Russian).
6. R.N. Wright. Wire Technology, Process Engineering and Metallurgy, Butterworth-Heinemann, Elsevier, 2011, p. 320.
7. N. Zhangabay, U. Suleimenov, A. Utelbayeva, S. Buganova, A. Tolganbayev, K. Galymzhan, S.

Dossybekov, K. Baibolov, R. Fediuk, M. Amran, B. Duissenbekov, A. Kolesnikov. Experimental research of the stress-strain state of prestressed cylindrical shells taking into account temperature effects, Case Studies in Construction Materials, 18, 2023, e01776.
8. G. Raab, R. Valiev, T. Lowe, Y. Zhu, Continuous processing of ultrafine grained A1 by ECAP-Conform, Materials Science and Engineering A, 382, 2004, 30-34.
9. N. Zhangabay, B. Sapargaliyeva, U. Suleimenov, K. Abshenov, A. Utelbayeva, A. Kolesnikov, K. Baibolov, R. Fediuk, D. Arinova, B. Duissenbekov, A. Seitkhanov, M. Amran, Analysis of Stress-Strain State for a Cylindrical Tank Wall Defected Zone, Materials, 15, 2022, 5732.
10. N. Zhangabay, U. Suleimenov, A. Utelbayeva, A. Kolesnikov, K. Baibolov, K. Imanaliyev, A. Moldagaliyev, G. Karshyga, B. Duissenbekov, R. Fediuk, M. Amran, Analysis of a Stress-Strain State of a Cylindrical Tank Wall Vertical Field Joint Zone, Buildings, 12, 2022, 1445.
11. D.G. Emaleeva, G.C. Gun, M.V. Chukin, Increase of Mechanical Properties of Steel Wire by Formation of Submicrocrystalline Structure of Surface Coating in the Process of Equal Channel Angular Drawing, Abstracts of International Symposium "Bulk Nanostructured Materials: from Fundamentals to Innovations", International Scientific, 2007, 134-135.
12. G.S. Gun, M.V. Chukin, D.G. Emaleeva. Investigation of the Formation of Submicrocrystalline Surface Structure in Steel Wire with the Aim of Improving Its Mechanical Properties, Bulletin of G.I. Nosov MSTU, 3, 2007, 84-86.
13. D.G. Emaleeva, M.V. Chukin, Influence of Heat Treatment on the Structural Evolution and Properties of Steel Wire during Extension in Bent Uniform Channels, Bulletin of G.I. Nosov MSTU, 2, 2008, 70-71.
14. M.V. Chukin, A.G. Korchunov, E.M. Golubchik, Continuous deformational nanostructuring of wire on the basis of technological inheritance, Bulletin of G.I. Nosov MSTU, 4, 2012, 61-65.
15. M. Polyakova, A. Gulin, D. Constantinov, Investigation of microstructure and mechanical properties of carbon steel wire after continuous method of deformational nanostructuring, Appl. Mechan. Mater, 436, 2013, 114-120.
16. H. Dyja, L. Lesik, A. Milenin, S. Mróz, Theoretical and experimental analysis of stress and temperature distributions during the process of rolling bimetallic rods, J. Mater. Process. Technol, 125-126, 2002, 731-735.
17. P. Eslami, A. Karimi Taheri, An investigation on diffusion bonding of aluminum to copper using equal channel angular extrusion process, Materials Letters, 65, 2011, 1862-1864.
18. I.E. Volokitina, A.V. Volokitin, Evolution of the Microstructure and Mechanical Properties of Copper during the Pressing-Drawing Process, Phys. Met. Metallogr., 119, 2018, 917-921.
19. I. Volokitina, A. Volokitin, A. Naizabekov, S. Lezhnev, E. Panin, Microstructure of bimetallic wire in the "ECAP-drawing" process, J. Chem. Technol. Metall., 56, 2021, 857-866.
20. I. Volokitina, Change in the microstructure and properties of steel-aluminum wire during "ECA-pressing-drawing" process, J. Chem. Technol. Metall., 57, 3, 2022, 631-636.
21. I. Volokitina, N. Vasilyeva, R. Fediuk, A. Kolesnikov, Hardening of Bimetallic Wires from Secondary Materials Used in the Construction of Power Lines, Materials, 15, 2022, 3975.
22. I. Volokitina, A. Volokitin, A. Naizabekov, E. Panin, FEM-study of bimetallic wire deformation during combined ECAP-drawing, J. Chem. Technol. Metall., 56, 2021, 410-416.
23. I.E. Volokitina, A.V. Volokitin, A.B. Naizabekov, Ye. Panin, FEM modeling of bimetallic billet deformation by the combined "EBSD-pressing-drawing" process, International scientific conference Machines, Technologies, Materials, Bulgaria, 2020, 41-44, (in Russian).